

The Galactic Stellar Disc‡

S Feltzing¹, T Bensby²

¹ Lund Observatory, Box 43, SE-221 00 Lund, Sweden

² European Southern Observatory, Alonso de Cordova 3107, Vitacura, Casilla 19001, Santiago, Chile

E-mail: sofia@astro.lu.se

Abstract. The study of the Milky Way stellar discs in the context of galaxy formation is discussed. In particular we explore the properties of the Milky Way disc using a new sample of about 550 dwarf stars for which we have recently obtained elemental abundances and ages based on high resolution spectroscopy. For all the stars we also have full kinematic information as well as information about their stellar orbits. We confirm results from previous studies that the thin and the thick disc have distinct abundance patterns. But we also explore a larger range of orbital parameters than what has been possible in our previous studies. Several new results are presented. We find that stars that reaches high above the galactic plane and have eccentric orbits show remarkably tight abundance trends. This implies that these stars formed out of well mixed gas that had been homogenized over large volumes. We find some evidence that point to that the event that most likely caused the heating of this stellar population happened a few billion years ago. Through a simple, kinematic exploration of stars with super-solar $[\text{Fe}/\text{H}]$ we show that the solar neighbourhood contains metal-rich, high velocity stars that very likely are associated with the thick disc. Additionally, the HR1614 moving group and the Hercules and Arcturus stellar streams are discussed and it is concluded that, probably, a large fraction of the so far identified groups and streams in the disc are the result of evolution and interactions within the stellar disc rather than being dissolved stellar clusters or engulfed dwarf galaxies.

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1. Introduction

The formation and evolution of galaxies is a key topic in contemporary astrophysics and a major driver for large observational facilities, such as the E-ELT, as well as extra-galactic surveys, one example being the Sloan Digital Sky Survey (SDSS). However, also the study of the very local universe in the form of the Milky Way and the Local Group are important in the context of galaxy formation. Indeed, Λ CDM, the currently most successful theory for the formation of large scale structure in the universe (Springel

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et al. 2006), meets with some important challenges when the smallest scales are being studied (Freeman & Bland-Hawthorn 2002, Diemand et al. 2008). These tests include questions relating for example to the number of dwarf galaxies and the formation and evolution of disc systems in spiral galaxies.

The formation and survival of disc galaxies within Λ CDM has recently been the focus of several investigations (Read et al. 2008, Hopkins et al. 2008, De Rossi et al. 2008). Given the hierarchical nature of the build up of galaxies within Λ CDM it seems natural that the formation of old discs might be a problem as what today is a giant galaxy must have suffered a bombardment of merging blocks over its lifetime. However, recent studies imply that the effects might not be as severe as initially thought. Two major issues have recently been discussed. De Rossi et al. (2008) investigated the merger trees for Milky Way like halos in the Millennium Simulation[§] and found that a majority of these indeed had very calm merger histories – allowing a build up of discs that would not be destroyed by major mergers. Although the large scale structure simulations can give us the number of mergers and interactions that a galaxy experiences throughout the age of the universe the effect that a merger or close interaction can have on a baryonic disc needs to be modeled separately in order to fully understand the damage in e.g. the form of heating of a pre-existing thin stellar disc to a thick disc. Hopkins et al. (2008) studied the heating effect of mergers on a large disc and found that the merger rate could be higher than previously thought without destroying the disc. The major reason for the increased number of allowed, non-destructive mergers is the fact that previous studies, that showed that smaller numbers already destroyed the disc, have not taken the full range of possible orbital parameters for merging satellites into account. By allowing for all types of orbits as well as using realistic sizes for the halos of the merging galaxies (as realized in cosmological simulations) Hopkins et al. (2008) found that the Milky Way could have had about 5 to 10 1:10 mass-ratio mergers since $z \sim 2$, which is in agreement with cosmological simulations.

We are thus in a situation where the simulations indicate on the one hand that Milky Way like galaxies must live in unusual places in the Universe in order to survive, on the other hand other types of modeling indicate that a Milky Way can survive a “typical” cosmological environment. The study of both local galaxies as well as galaxies far away can thus provide valuable data to constrain future modeling.

There is mounting observational evidence that disc galaxies exist at high redshifts. A recent result is the study of velocity maps for 11 galaxies at $z \sim 2$ by Shapiro et al. (2008) using the integral field spectroscopy instrument SINFONI on VLT. Their observations show that more than half of the galaxies in their sample have not suffered any recent major merger and the galaxies show ordered disc motions in the $H\alpha$ gas. The dynamical masses of these galaxies are large, $10^{10-11} M_{\odot}$. Several other studies have also shown the existence of both old stars as well as solar metallicities at similar redshifts. Two examples are given by Stockton et al. (2004) and Shapley et al. (2004).

[§] A description of the simulations as well as access to the publicly available database from the simulation can be found at <http://www.mpa-garching.mpg.de/millennium/>

In the more nearby universe thick discs have been shown to be near ubiquitous in edge-on galaxies (Yoachim & Dalcanton 2006, and references therein). In a recent study Yoachim & Dalcanton (2008), using Lick indexes, study the ages and metallicities of the stellar populations in a sample of edge-on galaxies with thick discs and found that the extra-planar regions in these galaxies are systematically older and less metal-rich than the stellar population in the mid-plane.

The most nearby disc system we can study is that in the Milky Way galaxy. The Milky Way has two stellar discs – one thick and one thin. These two discs differ in their properties. In particular, the thick disc is older and less metal-rich than the thin disc (Freeman & Bland-Hawthorn 2002). The thick disc also rotates more slowly around the centre of the Galaxy than the thin disc. The so called asymmetric drift is $\sim 50 \text{ km s}^{-1}$ for the thick disc and $\sim 15 \text{ km s}^{-1}$ for the thin disc (Freeman & Bland-Hawthorn 2002). The thick disc is generally thought to have a scale-height about 3 times larger than that of the thin disc. However, the exact scale-height of the thick disc as well as the local normalization in the solar neighbourhood, i.e. how many thick disc stars there are per thin disc star, is still not well-established. The values determined for the scale height for the thick disc found in the literature ranges from 600 pc to more than 1600 pc and the local normalization from 12% to about 2%. A compilation of the various determinations of the thick disc scale height as well as its local normalization can be found in Árnadóttir et al. (2008).

In the context of galaxy formation and as tests of models of galaxy formation it is important to establish the properties of a disc system of the type observed in the Milky Way. Studies of nearby galaxies as well as galaxies at higher redshifts show evidence for old, well-ordered gas and stellar discs. Some of these discs are also thick. The study of the Milky Way discs thus provides the very local example of such a system.

2. Kinematics, orbital parameters and elemental abundances

One of the first studies to systematically explore the potential of combining elemental abundances for stars with detailed knowledge about their ages, kinematics and orbital parameters was done by Edvardsson et al. (1993). A major outcome of this work was to firmly establish that the Milky Way disc, in fact mainly the thin disc, shows tight and well defined abundance trends for a large range of elements, such as Si, Ca, and Ni.

In 1997 the Hipparcos catalogue became available (Perryman et al. 1997). Combining this catalogue of parallaxes and proper motions with radial velocities from the literature it became possible to trawl large databases for stars with kinematics typical of the thin and the thick discs. Bensby et al. (2003) used this possibility and constructed two samples of F and G dwarf stars representative of the thin and the thick discs and showed that these two stellar samples differ. For example, the stars in the thick disc are more enhanced in [O/Fe], at a given [Fe/H], than the stars in the thin disc, figure 1. A first, simplistic, interpretation of the trend found for the thick disc stars is that the thick disc shows evidence of contribution by SNIa to its chemical evolution

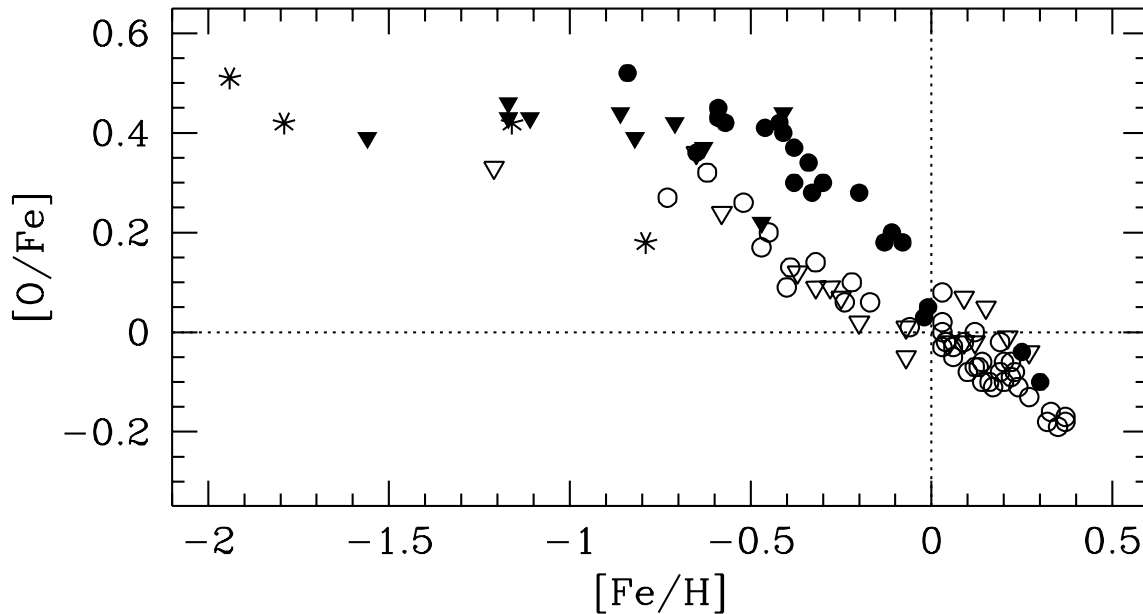


Figure 1. Oxygen abundances for stars with kinematics typical of the thin disc (\circ) and of the thick disc (\bullet) (Bensby et al. 2004) and stars with kinematics typical of the thin disc (∇), the thick disc (filled triangles) and halo ($*$) (Nissen et al. 2002). The data from Bensby et al. (2004) is based on observations of the [OI] line at 630.0 nm with the Coudé Echelle Spectrograph (CES) on the ESO 3.6m. The observations used the highest resolving power of the CES ($R \simeq 215\,000$) and the spectra have very high signal-to-noise (≥ 400).

as evidenced by the presence of the “knee” in the $[\text{O}/\text{Fe}]$ vs. $[\text{Fe}/\text{H}]$ trend. This trend is typically interpreted such that the constant $[\text{O}/\text{Fe}]$ is the result of enrichment of the interstellar gas from SN II. These supernovae form both oxygen and some iron and when the star forming gas sees the integrated enrichment from several supernovae the result is a constant oxygen to iron ratio. Iron is also produced in SN Ia but oxygen is not. Hence, when SN Ia start to contribute to the enrichment of the interstellar medium the oxygen to iron ratio will decrease in the subsequently formed stars. The time-scale for SN Ia are not firmly established, however, it is not only the life-time for a single object that is of interest but more so the formation rate of these types of systems and then their integrated effect on the chemical enrichment. The lifetimes for SN II are short and it is generally expected that the SN Ia enrichment happens on a longer time-scale, however, in certain cases it can also happen on time-scales shorter than the canonical one billion years. For a deeper discussion of these issues and further references see the recent lecture notes by Matteucci (2008).

An obvious limitation in the identification of thin and thick disc stars through the kinematic probabilities as used in e.g. Bensby et al. (2003) is that the interpretation requires that a star’s history is, at least to some extent, retained in its current kinematic properties. In this context the study by Fuhrmann are important (Fuhrmann 2008,

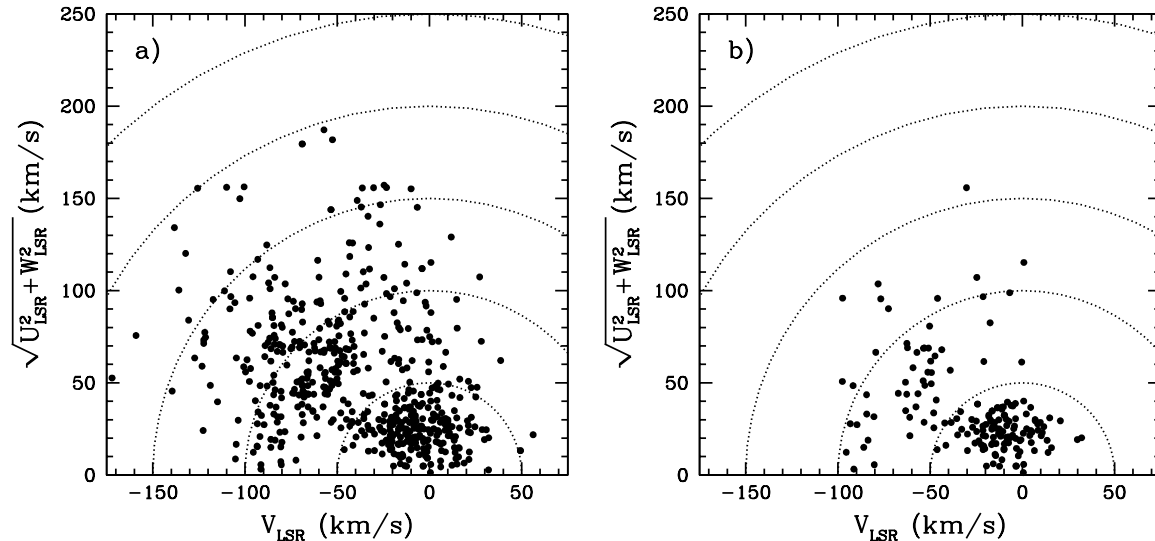


Figure 2. **a.** Toomre diagram for the whole sub-sample of ~ 550 stars. **b.** Toomre diagram only for stars with $[\text{Fe}/\text{H}] > 0$. In both panels the concentric circles, shown with dotted lines, indicate a constant total velocity in steps of 50 km s^{-1} .

Fuhrmann 1998). He studied a volume limited sample ($d < 25 \text{ pc}$) of dwarf stars in a narrow temperature range (essentially late F and early G dwarf stars). The sample selection does not include any consideration of the kinematic properties of the stars. The stars in this volume limited sample show two clear, and separate trends for $[\text{Mg}/\text{Fe}]$ as a function of $[\text{Fe}/\text{H}]$. Essentially, there is one set of stars that are enhanced in $[\text{Mg}/\text{Fe}]$ and one that is not. The stars that are enhanced in $[\text{Mg}/\text{Fe}]$ fall on a plateau in the abundance diagram and the most metal-rich of them have $[\text{Fe}/\text{H}]$ of about -0.3 dex . Fuhrmann identifies these stars with the thick disc (compare the enhanced $[\text{O}/\text{Fe}]$ in figure 1 for the, kinematically identified, thick disc stars). The other trend contains stars that are younger and with lower $[\text{Mg}/\text{Fe}]$. The $[\text{Mg}/\text{Fe}]$ as a function of $[\text{Fe}/\text{H}]$ trend for these stars is comparable to the oxygen trend for the kinematically selected thin disc stars in figure 1.

Most importantly, the study by Fuhrmann (2008) shows that a volume limited sample gives the same resulting abundance trends as found in the kinematically selected samples. Fuhrmann’s study thus provides a validation of the selection techniques developed in the literature. These techniques use various kinematic criteria that are turned into membership probabilities that are then used to identify the thin and thick disc stars. Examples include the methods developed in the following studies Gratton et al. (2003), Reddy et al. (2003), Bensby et al. (2003), Venn et al. (2004), Soubiran & Girard (2005), and Reddy et al. (2006).

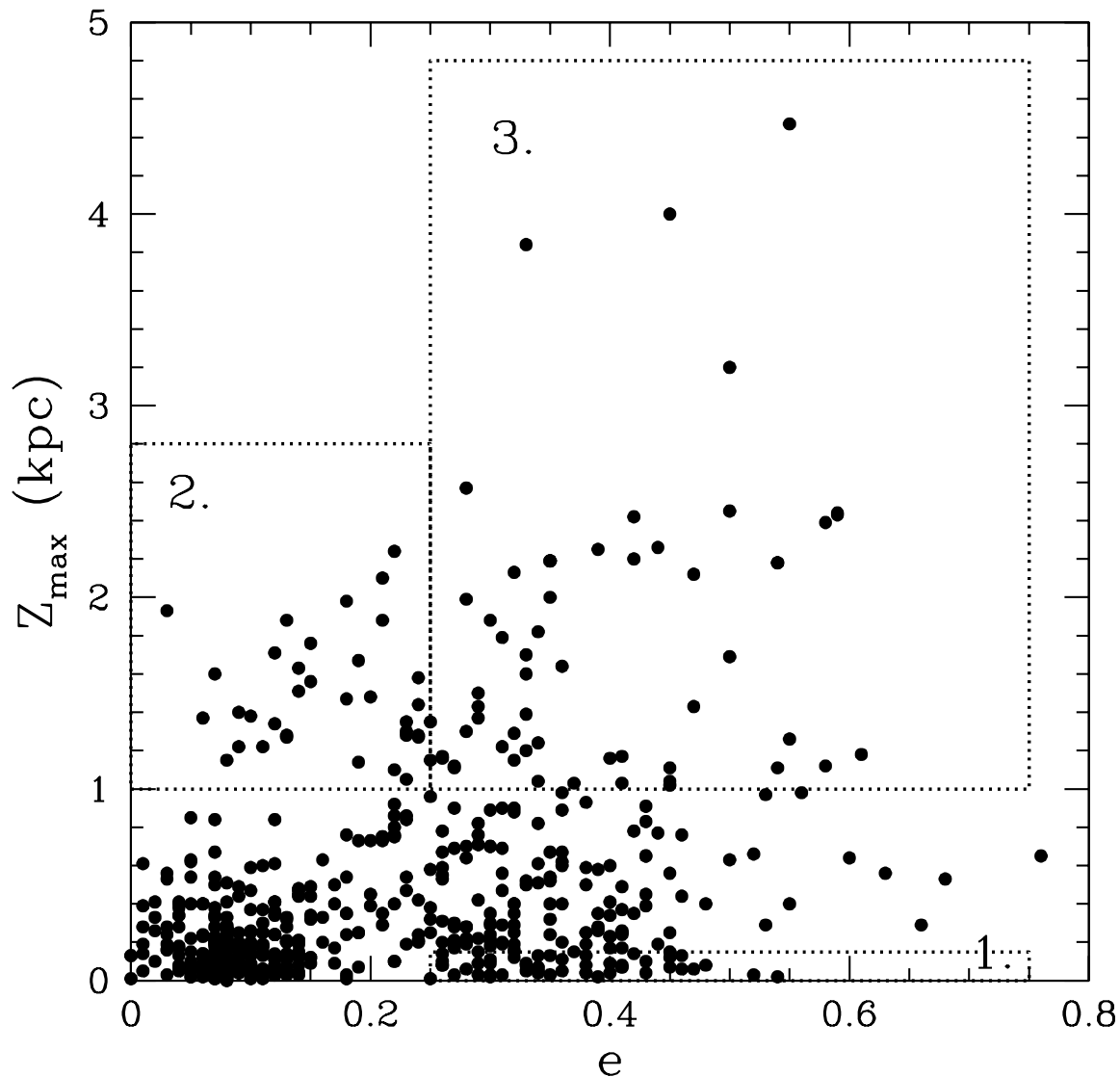


Figure 3. Z_{max} as a function of e for the stellar sample. Three boxes show the outlines of the parameter spaces considered in figure 5 and section 2.1. The numbers for the boxes corresponds to the same numbers for the panels in figure 5 and 8. The orbital parameters are taken from Nordström et al. (2004).

2.1. A new stellar sample

We have obtained high-resolution, high S/N spectra for about 900 dwarf stars. The data have been obtained with several spectrographs but in general $S/N > 250$ and $R \geq 65,000$ (apart from the sub-set of stars originally observed with FEROS (Bensby et al. 2003) which have $R = 48,000$). In this publication we present the kinematic properties and some elemental abundances as well as discuss the stellar ages for a sub-sample of about 550 F and G dwarf stars. We employ the same methods of abundance analysis as outlined in Bensby et al. (2003). However, in the present analysis we allow for enhancement of

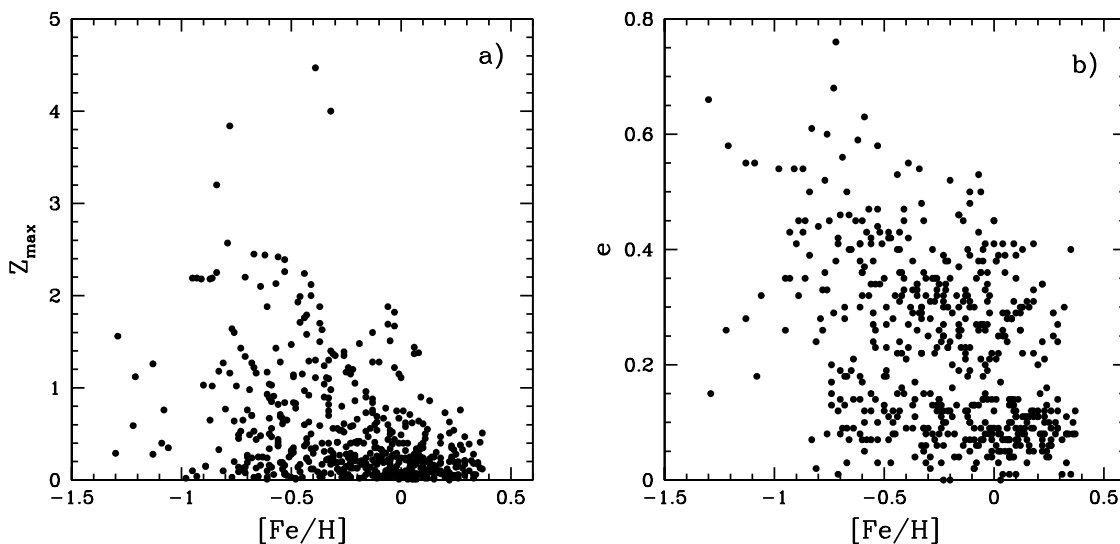


Figure 4. **a.** Z_{max} as a function of $[Fe/H]$ for our sample. **b.** e as a function of $[Fe/H]$ for our sample. The apparent gap at $e \sim 0.2$ is an artifact resulting from the selections of the various sub-samples that make up the final sample (see discussion in section 2.1). The orbital parameters are taken from Nordström et al. (2004).

α -elements in the model atmospheres and we use a somewhat more automatic process to determine the stellar parameters. The surface gravity and age determinations are still based on the Hipparcos parallax (Perryman et al. 1997) but now using the parallaxes from the new reduction provided by van Leeuwen (2007). For the present discussion we use the orbital parameters from Nordström et al. (2004). However, given that for some stars the new parallaxes and proper motions are sufficiently different from those in the original Hipparcos catalogue we will re-calculate them. We have already derived new stellar ages based on our own effective temperatures and the new parallaxes. For the derivation of stellar ages we use the Yonsei-Yale isochrones (Kim et al. 2002, Demarque et al. 2004).

Figure 2 shows the kinematic properties of the ~ 550 stars we present here. The full sample is built from several sub-samples. Each of these sub-samples have originally been selected to study a particular issue, e.g. how metal-rich can the thick disc be (Bensby, Zenn, Oey & Feltzing 2007). The result is a somewhat uneven distribution in velocity space. This is perhaps more obvious in figure 3 which shows the maximum height above the galactic plane (Z_{max}) that a star reaches as a function of the ellipticity of the orbit for the star (e). One aspect of our sample that sets it apart from e.g. the studies by Reddy et al. (2006) and Reddy et al. (2003) is that we cover a wider range of orbital parameters. For example our sample includes stars on low e orbits with low $[Fe/H]$ (chosen to study the metal-weak thin disc) as well as stars with super-solar $[Fe/H]$ and high e (chosen to study the metal-rich thick disc). Neither of these types of stars have been systematically included in previous studies. In fact in some studies they are lacking

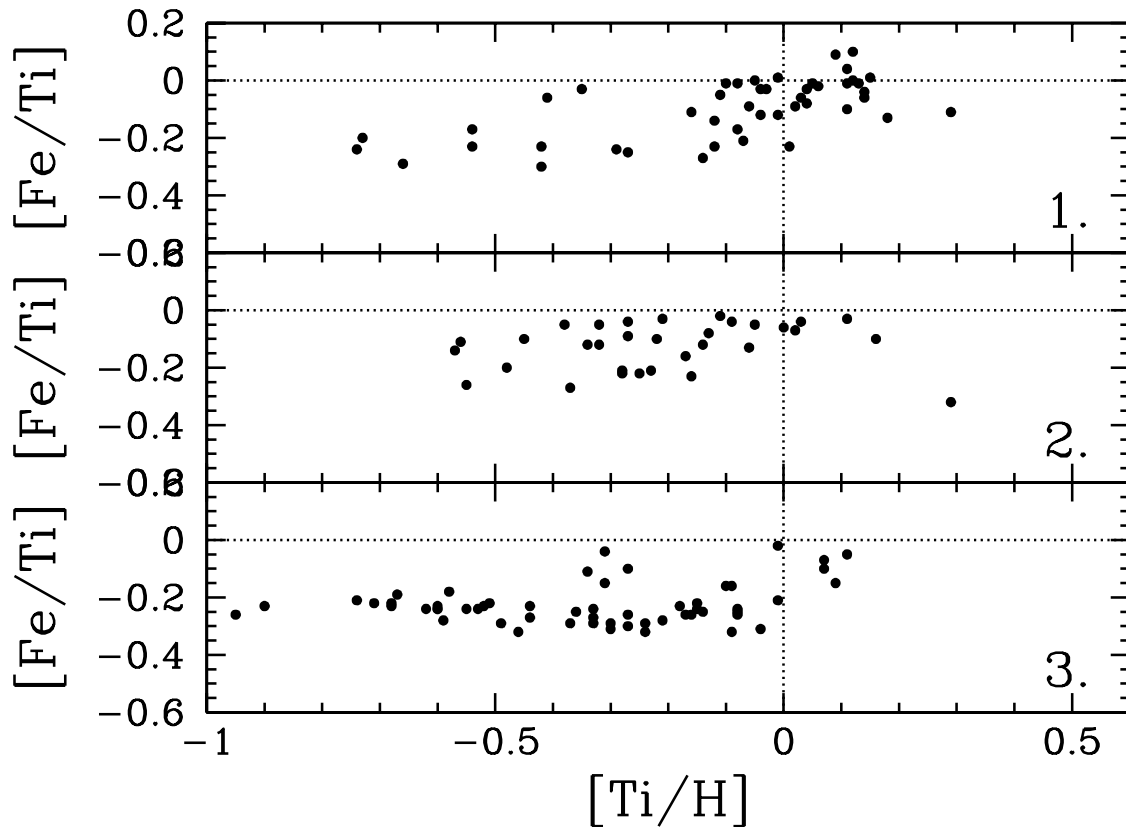


Figure 5. $[\text{Fe}/\text{Ti}]$ vs. $[\text{Ti}/\text{H}]$ for the three samples defined in figure 3. The numbering of the panels corresponds to the numbering of the boxes in figure 3.

all together and the inclusion of them in our study has enabled us to explore a wider range of the parameter space (compare figure 4).

2.2. Exploration of the Milky Way stellar disc

We start our exploration of the Milky Way by considering the $Z_{\text{max}}-e$ space. In figure 3 three areas of interest are indicated. All three boxes contain what could be deemed thick disc stars. Box 1 includes the stars that move on very eccentric orbits but have low W_{LSR} , Box 2 stars that have low eccentricities but high W_{LSR} , and Box 3 includes the stars that have both high e and high W_{LSR} . Figure 5 then shows the elemental abundance trends for the stars that fall in these three boxes. We have chosen to show $[\text{Fe}/\text{Ti}]$ vs $[\text{Ti}/\text{H}]$ as the separation between e.g. thin and thick disc tends to be most obvious for this combination of elements but also because Ti is essentially made in SN II whilst Fe comes from both SN II and Ia. Hence we now have a clearer tracer of time on the x -axes than when using Fe as the reference element.

The trends for the three boxes differ. Box 1 and 3 are quite similar, although stars in Box 3 show a more distinct trend. For both samples we see a flat trend with a constant $[\text{Fe}/\text{Ti}]$ at about -0.25 dex that extends from $[\text{Ti}/\text{H}]$ of -1 to 0 dex. The trend

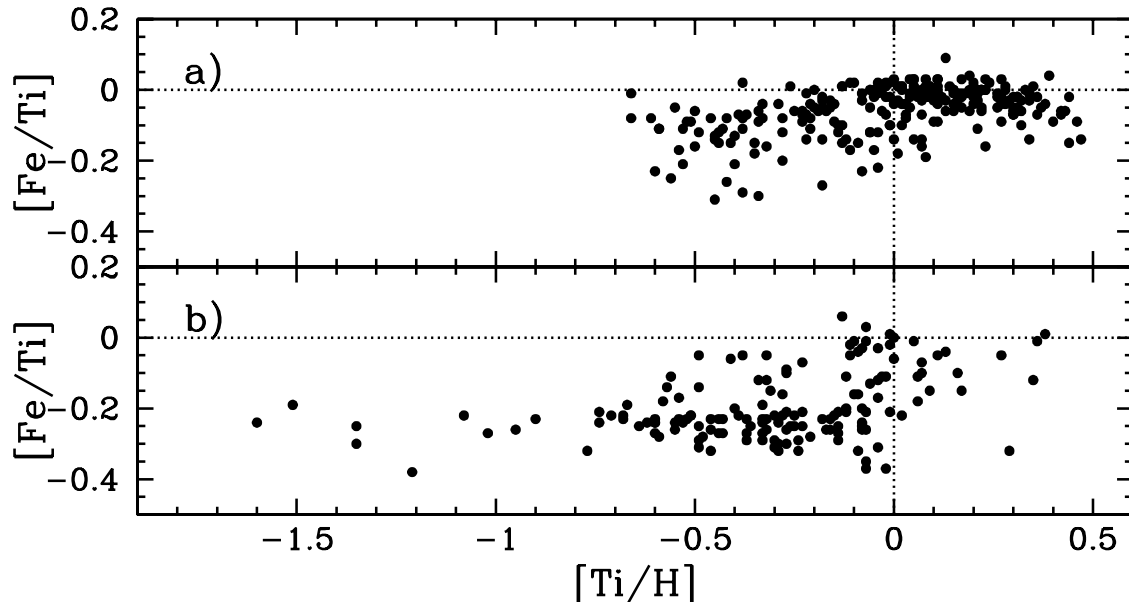


Figure 6. $[\text{Fe}/\text{Ti}]$ vs. $[\text{Ti}/\text{H}]$ for **a.** stars that are ten times more likely to be thin than thick disc and **b.** stars that are ten times more likely to be thick than thin disc stars. The separation is based on probabilities calculated according to the prescriptions in Bensby et al. (2003).

for the stars in Box 3 shows a possible upturn in $[\text{Fe}/\text{Ti}]$ after $[\text{Ti}/\text{H}] = 0$. For the stars in Box 1, however, there is a clear upturn around $[\text{Ti}/\text{H}] = 0$. In contrast, the stars from Box 2 show a fairly flat distribution with a higher $[\text{Fe}/\text{Ti}]$ (mean value of roughly -0.1 dex) and a larger spread in abundance ratios.

The tightness of the trend seen for the stars in Box 3 is quite remarkable. The star-to-star scatter is less than 0.1 dex over a range of 1 dex (omitting four stars at $[\text{Ti}/\text{H}] = -0.3$). Such a trend can only be achieved if the stars formed out of a gas that was well mixed (Gilmore & Wyse 2004). Moreover, taking the orbital parameters for the stars in Box 3 into account this implies that the gas these stars formed out of had not only seen the average effect of about a hundred supernovae but that the mixing was efficient over a volume spanning several kpc.

The trend for the stars in Box 3 and 1 can be compared with the trend found for the thick disc using the selection criteria in Bensby et al. (2003). Their selection method is based on the fact that the thin disc, thick disc, and halo rotate at different speeds around the centre of the Galaxy and that for each of these stellar populations we know the velocity dispersions in UVW. Using this information it is possible to calculate a probability that a star belongs to one of the three components. These probabilities can then be compared and very likely thin and thick disc members, respectively, can be picked. Figure 6b shows the thick disc $[\text{Fe}/\text{Ti}]$ vs. $[\text{Ti}/\text{H}]$ abundance trend using this selection technique. Only stars that are ten times more likely to be thick than thin disc stars are shown. The trend found for the thick disc with this selection is more scattered

in appearance but has the same basic features as the much more well-defined trend found in Box 3. This is, most likely, an indication of the limitations of the statistical techniques we use to select the thin and the thick disc stars. However, also here we see an essentially flat and rather tight abundance trend spanning over one dex in $[\text{Ti}/\text{H}]$. For $-0.6 < [\text{Ti}/\text{H}] < -0.2$ there is some likely thin disc contamination. Disregarding these stars we are again led to the conclusion that the thick disc stars must have formed out of well-mixed gas that had seen the integrated effect of many supernovae.

The elemental abundance trend for stars selected in Box 2, figure 3, can then be compared with that for stars selected to be very likely thin disc stars, as shown figure 6a. Although the number of stars in Box 2 are few and hence the trend not so well established as for the thin disc sample it is clear that the two trends agree extremely well and that both are distinct from that of the thick disc as well as being distinct from the trends found for the stars in Box 3 and 1.

2.2.1. Stellar ages The distributions of the ages for the stars selected in the three boxes and for the thin and the thick disc are shown in figure 7. We only include stars for which the age could be determined with a relative error less than 30%. The thin and the thick discs show overlapping distributions but with distinct mean ages, the thick disc is on average older than the thin disc. The thin and the thick discs are selected according to the same criteria as for the abundance trends shown in figure 6. We also show the age distribution for stars on very circular, planar orbits ($0 < e < 0.15$ and $Z_{\text{max}} < 0.5$ kpc). This could be regarded as a very conservative thin disc sample. It is reassuring to see that the age distribution for those stars is essentially the same as for our thin disc sample.

The stars from Box 2 show an age distribution skewed to younger ages. Box 1 has an essentially flat age profile and Box 3 shows a distribution similar to that of the thick disc. The number statistics are low for Box 1 and 2 and any conclusions drawn from this should be regarded as tentative and needs confirmation with larger samples. Our full sample of 900 stars indeed includes many more stars on such orbits that still needs to be analyzed and should help clarify the picture.

2.2.2. Additional evidence for well-mixed gas – Barium abundances Other elements also show tight abundance trends, further strengthening the suggestion that indeed (all or part of) the thick disc has formed from well-mixed gas. Figure 8 show the $[\text{Ba}/\text{Fe}]$ vs $[\text{Fe}/\text{H}]$ trends for the three boxes defined in figure 3. Again we see *very* tight abundance trends. A comparison with the trends for the thin and thick discs (same definition as used to create figure 6 and 9) shows that the trends in the three boxes mainly resemble those of the thick disc. The stars in Box 3 might have a tendency to show lower $[\text{Ba}/\text{Fe}]$ than the stars in Box 1 and 2. This is certainly the case for $[\text{Fe}/\text{H}]$ around -0.55 . However, some care is needed in the interpretation of figure 9a. In Bensby, Zenn, Oey & Feltzing (2007) we showed that at least some part of the apparent large scatter for the thin disc sample is due to what could be called an age-effect. It is the youngest stars

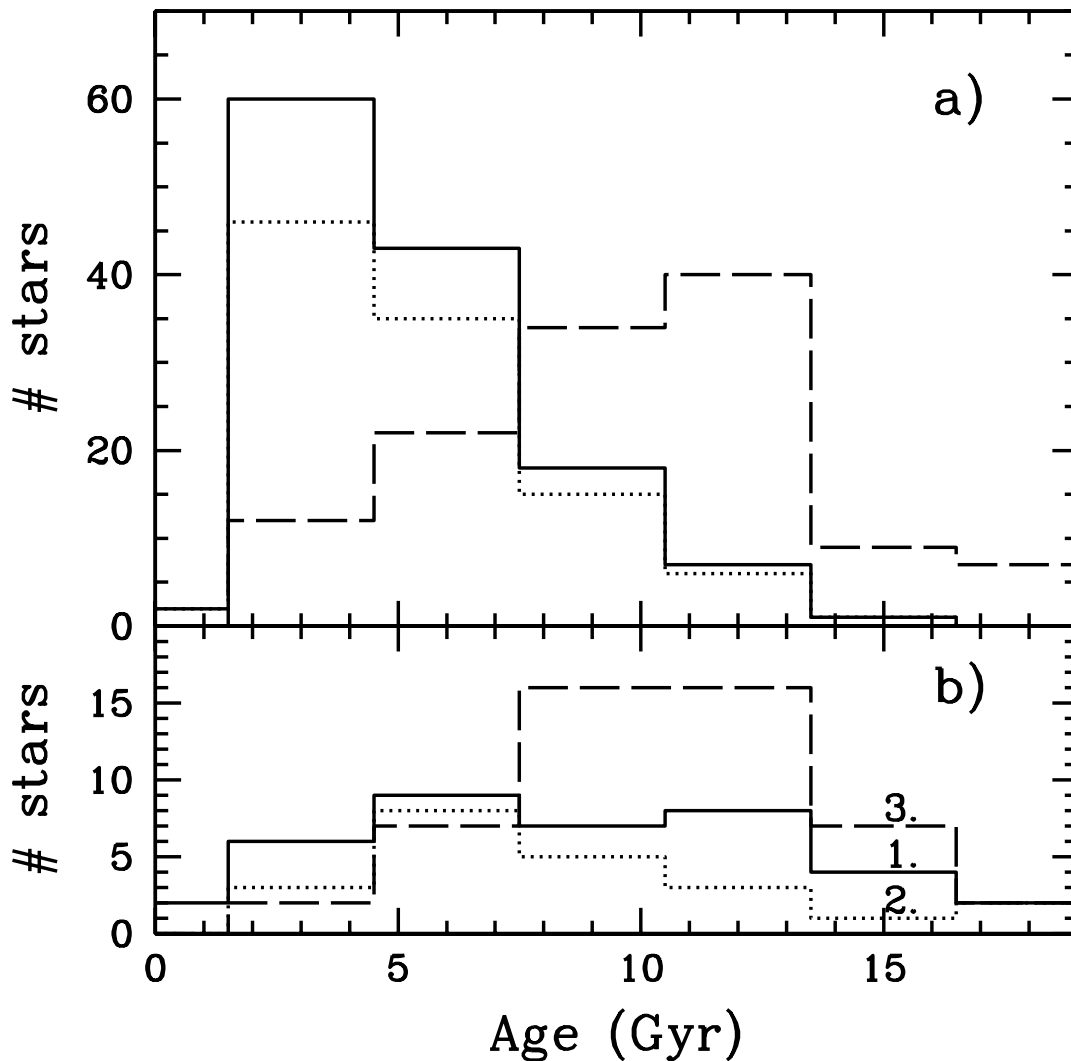


Figure 7. Distribution of stellar ages for the samples of stars for which the elemental abundance trends are shown in figure 6 and figure 5 and identified in figure 3. In these histograms we use the stars with “good” age determination. For the current sample this means that we have only included stars for which the internal, relative error in the age determination is less than 30%. **a.** Age distribution for the stars selected to be ten times more likely to be thin than thick disc stars is shown with a full line. The distribution for stars that are ten times more likely to thick than thin disc stars are shown with a dashed line (compare figure 6b). The dotted line shows the distribution for stars with $0 < e < 0.15$ and $Z_{\max} < 0.5$ kpc (compare figure 3). **b.** This panel shows the age distributions for the three stellar samples selected in Box 1 – 3 in figure 3 and for which the elemental abundance trends are shown in figure 5 and 8. The histograms are labeled with their respective box identification as used in those figures.

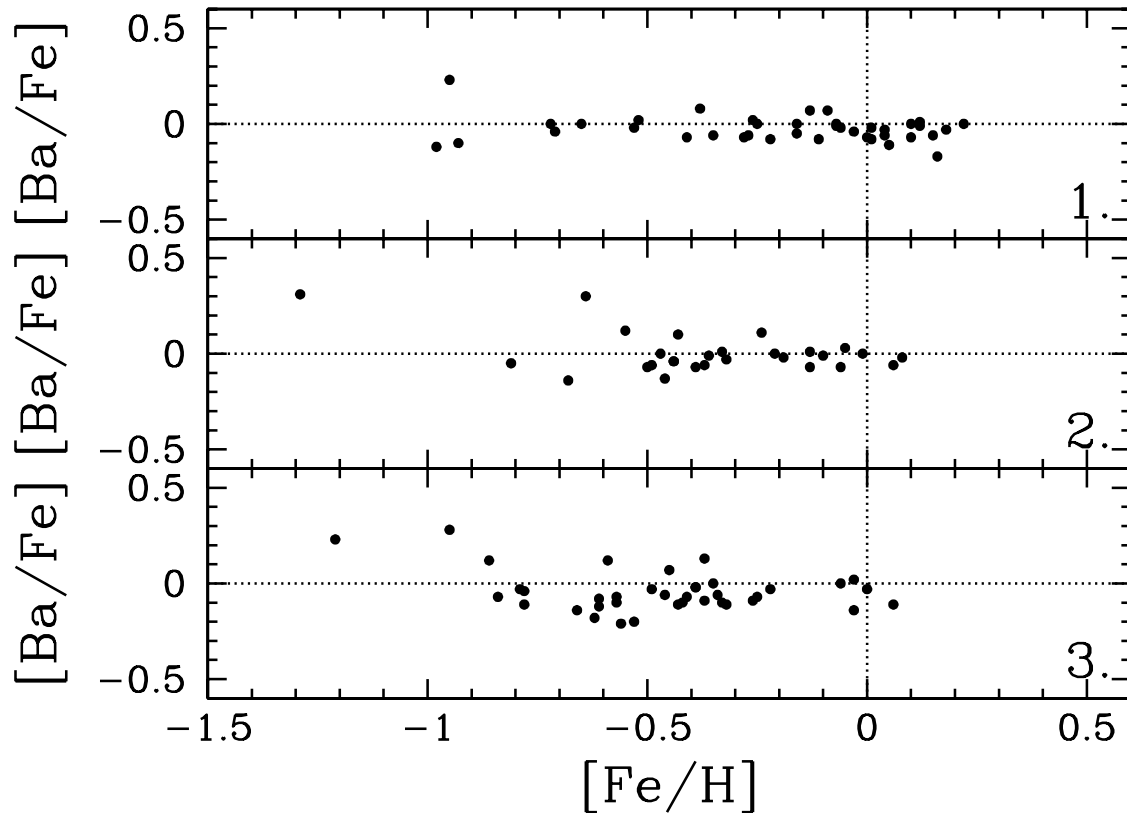


Figure 8. $[\text{Ba}/\text{Fe}]$ vs. $[\text{Fe}/\text{H}]$ for the three samples defined in figure 3. The numbering of the panels corresponds to the numbering of the boxes in figure 3. We do not include stars with only one Ba line measured or with large errors (we only select stars with $\sigma_{\text{line-to-line}}/n_{\text{lines}} < 0.075$).

that have the largest $[\text{Ba}/\text{Fe}]$, in fact, $[\text{Ba}/\text{Fe}]$ appears to be, for the last few billion years a monotonously increasing function of age. The older thin disc show a tight flat trend. Hence, the fact that the trend for Box 2 resembles that for the thick disc more than that of the thin disc is not necessarily in contradiction with the observations of the thin disc.

2.2.3. Discussion of Box 1 and 3 It is generally understood that the heating mechanisms that work in the plane, and thus cause higher eccentricity for the orbits, are different from those that heat the disc vertically. The difference manifest itself for example in that there is considerable structure in the U_{LSR} and V_{LSR} plane but the W_{LSR} velocity shows a smooth distribution (Holmberg et al. 2007). As summarized in Holmberg et al. (2007) the heating mechanisms responsible for the vertical heating is observed to be more efficient than what simulations of heating from within the disc can produce (e.g. heating from molecular clouds and black holes).

The effect of a merger depends not only on the size of the in-falling galaxy but also on its orbit (Hopkins et al. 2008, Read et al. 2008). Read et al. (2008) explored a

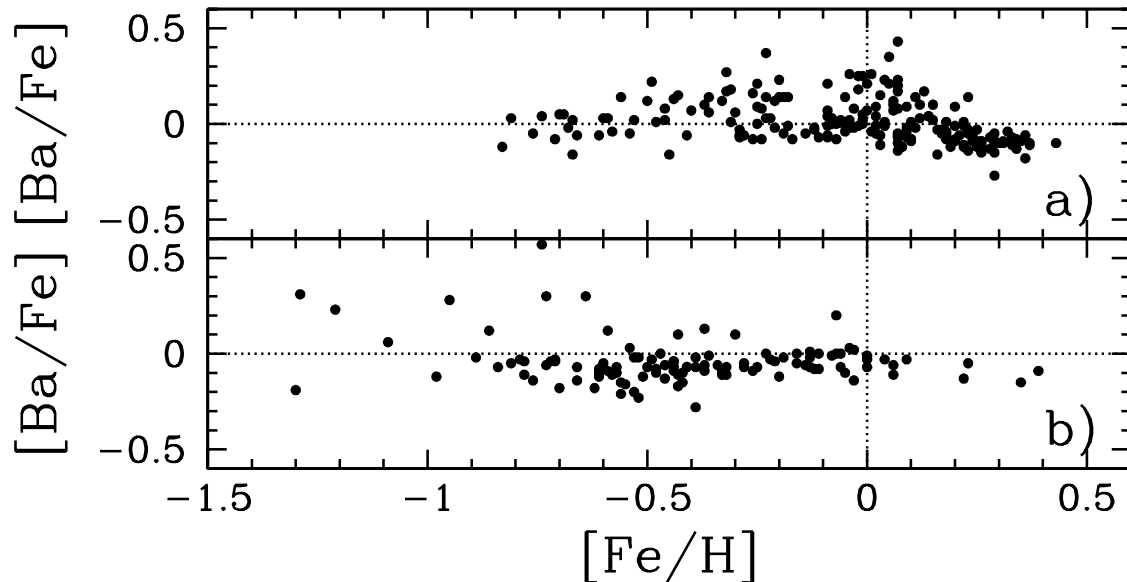


Figure 9. $[\text{Ba}/\text{Fe}]$ vs. $[\text{Fe}/\text{H}]$ for **a.** stars that are ten times more likely to be thin than thick disc and **b.** stars that are ten times more likely to be thick than thin disc stars. The separation is based on probabilities calculated according to the prescriptions in Bensby et al. (2003). We do not include stars with only one Ba line measured or with (we only select stars with $\sigma_{\text{line-to-line}}/n_{\text{lines}} < 0.075$).

range of parameters and found that it is possible to create stellar thick discs that are qualitatively similar to that seen in the solar neighbourhood in the Milky Way.

We have investigated Z_{max} as a function of age for the stars in Box 1 – 3 as well as the thin and the thick disc stars. There does not appear to be any particular trend such that older stars on average reach higher heights above the galactic plane. In the thick disc sample there might be a slight tendency for this but over all age and Z_{max} do not show any obvious correlations. If the stars that now reach high above the galactic plane had acquired their high W_{LSR} velocities over time (i.e. through heating from within the disc itself) it would be natural to expect a correlation such that stars that reach high above the plane are also the oldest, i.e. the vertical velocity dispersion increases with age (Freeman & Bland-Hawthorn 2002). We do not appear to see that as manifested in the distribution Z_{max} as a function of age. Hence, a preliminary conclusion is that the major reason for the observed W_{LSR} is not heating over time within the disc. This is in agreement with dynamical studies e.g. Hänninen & Flynn (2002). On the other hand, if the observed velocities are the result of a merger event then that must have happened quite late as also stars with ages of about 5 Gyr are equally well represented at the high latitudes as older stars. Hence it appears natural to invoke an “external” heating mechanism such as a major or minor merger to produce the observed velocity dispersion in the vertical direction.

The very tight abundance trends observed for Box 1 and 3, and especially for Box

3, in combination with the discussion above thus, tentatively, leads to the conclusion that what we see in these two Boxes is a stellar population that has been heated by a merger event. Box 1 could be expected to be made up of mixture of stars. It should then contain stars that has never been heated in the vertical direction but have suffered in-plane interactions that have put them on more eccentric orbits. Box 1 should then also contain stars that in fact belong to Box 3 (i.e. heated stars) and either providing the low velocity tail of that box or are stars that have lost their high W_{LSR} thanks to encounters. The event that heated this population should have happened a few billion years ago (keeping in mind that our age determinations *de facto* are of a relative not absolute nature).

2.2.4. The stars in Box 2 In Box 2 we find that stars that are on circular orbits (i.e. e is low) but that have high W_{LSR} show the same type of abundance pattern as found for stars on solar type orbits (see figure 5 and 6). This directly implies that indeed these high Z_{max} stars originate from the solar neighbourhood. It would seem natural to assume that these stars should be amongst the oldest stars with solar type U_{LSR} and V_{LSR} velocities. This is, however, not the case. The stars show a range of ages, just like the stars with high likelihood to be thin disc stars.

However, the stars in Box 2 show another feature – there are no stars with $[\text{Fe}/\text{H}]$ (or indeed $[\text{Ti}/\text{H}]$) above solar amongst them, whilst our thin disc sample has a large number of such stars (compare e.g. figure 9). Thus it appears that if the stars occupying Box 2 originally are stars from the solar neighbourhood with solar type orbits that has since been vertically heated this heating took place before the full chemical enrichment as seen in the thin disc took place. If the heating in the form of a merger is needed in order to explain the orbits of the stars in Box 2 this observations might thus indicate that this heating event took place some time ago. However, an answer to when would need detailed modeling of the chemical and dynamical evolution. Also, the number of stars in Box 2 is not very large and a larger sample should be gathered before firm conclusions can be made.

2.3. Orbit switching?

In figure 10a we show $[\text{Mg}/\text{Fe}]$ vs $[\text{Fe}/\text{H}]$ for the stars that are ten times more likely to be thin than thick disc stars. Although the general trend is of a single downward slope we find that there are a set of stars that appear to show essentially the same abundance trend but slightly “elevated”. In figure 10c we have marked the stars that are older than 9 Gyr. Clearly, the stars that are extra-enhanced in $[\text{Mg}/\text{Fe}]$ are the oldest stars. We have explored if other cuts in age would produce other distinct trends but have found none.

What is the origin of these stars? Could these stars have migrated from the inner disc? Could they be the remnants of an engulfed dwarf galaxy?

Sellwood & Binney (2002) showed that it is possible for stars to migrate significant

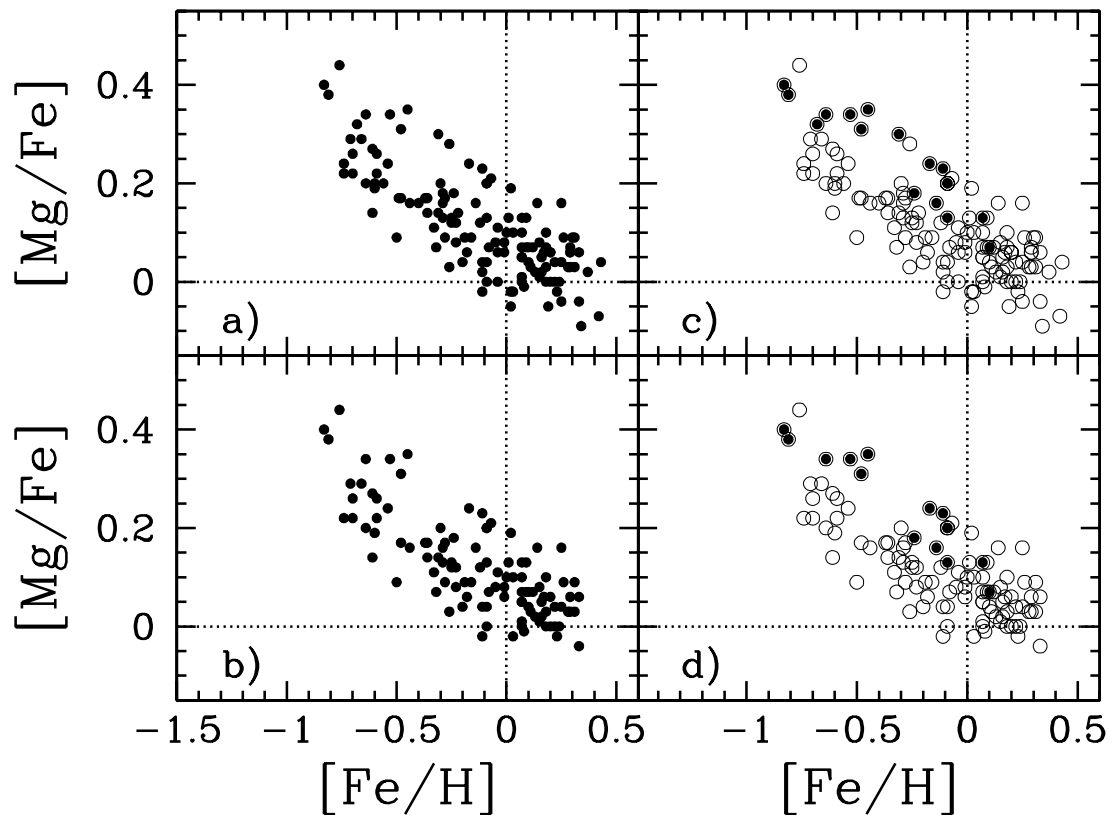


Figure 10. Sign of migration? **a.** Stars that are ten times more likely to be thin than thick disc star and which have relative errors in their age determinations less than 30%. **b.** Stars with $0 < e < 0.15$ and $Z_{\max} < 0.5$ kpc and relative errors in their age determinations less than 30%. **c.** same as **a.** but with stars with age larger than 9 Gyr marked with \bullet . **d.** same as **b.** but with stars with age larger than 9 Gyr marked with \bullet .

distances radially in the stellar disc. This means that stars that formed from promptly enriched gas in the inner disc can have migrated out to the solar radius. A recent simulation, investigating the truncation of stellar discs seen in other galaxies show the same effect (Roškar et al. 2008). The migration of stars would lead to a weakening of any age-metallicity relation in the stellar disc and would, potentially, also confuse the elemental abundance trends as stars that are the result of star formation histories that have taken place at different positions in the Milky Way disc end up on orbits that are too similar to be distinguished kinematically. If the observed old, metal-rich stars with thin disc but elevated $[\text{Mg}/\text{Fe}]$ and thin disc kinematics actually originate in the inner disc then, if migration is a constantly on-going process, why are we seeing only one such trend? Does this imply that the orbit switching happens only sometimes and for short periods of time?

In spite of the intriguing possibilities discussed above it appears prudent to, for now, refrain from further speculations and conclude that the exact nature of these few

stars remains unclear and requires further investigations.

2.4. The metal-rich thick disc

In Bensby, Zenn, Oey & Feltzing (2007) we asked the question: “How metal-rich can the thick disc be?” For this very purpose we had selected a sample of metal-rich (as judged from metallicities based on photometry) stars with typical thick disc kinematics and obtained high-resolution ($R \simeq 65,000$), high signal-to-noise ($S/N \simeq 250$) spectra for F and G dwarf stars sampling the relevant parameter space (for details see Bensby, Zenn, Oey & Feltzing (2007) and Bensby et al. in prep.). The abundance analysis showed that indeed the stars are metal-rich. Using a combination of kinematic and abundance criteria we showed that stars with typical thick disc kinematics and typical thick disc abundance patterns reached solar metallicity. Moreover, these stars are also old. Older than stars with the same $[Fe/H]$ but with typical thin disc kinematics and typical thin disc abundance patterns.

In figure 2b the Toomre diagram for all stars with $[Fe/H] > 0$ is shown. A large fraction of the stars are clustered together with kinematics akin to that of the sun (the over-density centred at $V_{LSR} \simeq 0 \text{ km s}^{-1}$). But there are quite a few stars at $V_{LSR} < -50 \text{ km s}^{-1}$ (remember that the asymmetric drift of the thick disc is about -50 km s^{-1}), indeed there are stars all the way down to about -100 km s^{-1} and stars with high U_{LSR} and W_{LSR} velocities. Twelve of these stars would be selected as ten times more likely to be thick disc stars than thin disc stars using the scheme in Bensby et al. (2003). These stars have V_{tot} around 100 km s^{-1} or larger.

This simple, kinematic exploration of stars with super-solar $[Fe/H]$ shows that the solar neighbourhood contains metal-rich, high velocity stars that very likely are associated with the thick disc. Proper dynamical modeling of such stellar populations are necessary in order to fully understand the origin and nature of the thick disc.

3. Moving groups and stellar streams

The stars in the solar neighbourhood are not smoothly distributed in the $U_{LSR} - V_{LSR}$ plane. Indeed, significant sub-structure is present and several so called moving groups and stellar streams have been identified through detailed analysis of the *Hipparcos* data (Dehnen 1998, Famaey et al. 2005, Arifyanto & Fuchs 2006). However, the concept of moving groups is older than these investigations and was originally introduced by O. Eggen, although his definitions of the groups have been largely superseded by the work using the *Hipparcos* parallaxes.

The origin of these moving groups and stellar streams remain unclear. Are they evaporating stellar clusters, accreted dwarf galaxies or the result of secular evolution in the Milky Way disc? Studies of the elemental abundances and ages for the stars in the groups may hold the answer.

The Hercules and Arcturus stellar streams The presence of streams in the Milky Way disc, like the Hercules and Arcturus streams, has lead to the speculation that they may be the remnants of a minor merger, a dwarf galaxy that has been engulfed by the Milky Way disc and now is only visible as perturbations in the velocity field. Models of minor mergers show that the stars may indeed end up on orbits typical for the stars in these streams (Williams 2008). However, detailed dynamical modeling have instead attributed these streams to dynamical process in the Milky Way disc, probably partly driven by the presence of a bar in the central parts of the Galaxy (Dehnen 1998).

The Hercules stream was found to contribute about 6% of all stars in the solar neighbourhood (Famaey et al. 2005). The stream has a net drift relative to the local standard of rest of about $\sim 40 \text{ km s}^{-1}$ directed radially away from the galactic centre. It also has a assymetric drift similar to that of the thick disc. The Hercules stream is included in our sample and can be seen as an increase in the stellar density at $V_{\text{LSR}} < -60 \text{ km s}^{-1}$ in figure 2.

Two recent studies provide detailed abundance analysis of stars in these streams (Bensby, Oey, Feltzing & Gustafsson 2007, Williams 2008). In both cases neither stream show a distinct abundance or age pattern. Instead, the stars associated with the stream merges into the general trends found for the disc stars in general. In fact Bensby, Oey, Feltzing & Gustafsson (2007) find that the stars in the Hercules stream falls essentially on the two age-metallicity trends traced by their thin and thick disc samples, respectively.

The results from these studies thus imply that the two streams indeed are the results of dynamical evolution within the Milky Way disc itself rather than the merger of a smaller dwarf galaxy with the Milky Way.

The HR1614 moving group The HR1614 moving group was originally defined by Eggen, see for example Eggen (1992) and references therein. Recently, De Silva et al. (2007) obtained high resolution, high S/N spectra for members of the HR1614 moving group. Their abundance analysis revealed that indeed the stars within this group show extremely homogeneous elemental abundances. In fact, their sample contained a few field stars which were easily identifiable thanks to their discrepant abundances.

Hence, so far it is only the HR1614 moving group that has shown itself to be an homogeneous, single age, single abundance stellar population. The other groups appear to be the kinematic gathering of stars that have suffered secular evolution within the disc and are not the result of dissolving stellar clusters or captured satellite galaxies. These results are in accordance with a new study by (Antoja et al. 2008). They find that indeed the stars in most of the easily identifiable structures in the $U_{\text{LSR}} - V_{\text{LSR}}$ plane do not share a common age or metallicity, but instead show significant spreads in these parameters.

4. Summary

We have presented data for a new stellar sample, comprising some 550 F and G dwarf stars. These stars span a large range of orbital parameters and we have been able to explore the Milky Way stellar disc, as manifested in the solar neighbourhood, in some detail. In particular we find the following

- We find remarkably tight abundance trends for stars that reach high above the galactic plane and have eccentric orbits show
- A tentative interpretation of these abundance trends is that the gas that these stars formed out of must have been well mixed on large scales (on the order of kpc)
- We confirm previously found abundance trends for statistically selected samples of thin and thick disc stars

Additionally, we discuss the presence of a significant number of high-velocity stars with super-solar metallicities as well as a possible detection of stars that are tentative candidates for orbit switching, i.e. stars that were born on a circular orbit further in towards the galactic centre but now have been moved out to new, still circular, orbits in the solar neighbourhood.

Recent studies employing high resolution abundances analysis for so called moving groups and stellar streams are starting to fill an important gap in our knowledge about the origin of the “lumpy” parts of the velocity distributions in the Milky Way disc. The first results show that these groups and streams are an heterogeneous set of objects. The HR 1614 moving group show very coherent elemental abundances for its stars. This group of stars could definitely be found by using so called chemical tagging (Freeman & Bland-Hawthorn 2002). The Arcturus and Hercules streams on the other hand seem to simply be the result of dynamical processes within the stellar disc, perhaps powered by the bar. It remains important to explore additional groups and streams. These studies should be done in a differential manner to the general disc population in order to better understand their origin.

Extra-galactic observation provide more and more evidence for ordered old and metal-rich stellar and gaseous discs in large galaxies at high redshifts. Locally, in the Milky Way, we find that stars on “hot”, thick disc like orbits show extremely tight abundance trends indicating that they were formed out of gas that was well-mixed over large scales. Given that these stars, on average, also are old we are potentially seeing the local counterpart to those high redshift discs.

Finally, I would like to thank all the organizers of this meeting. You had truly managed to create a meeting in the spirit of Bengt Gustafsson’s multi-faceted achievements within and outside of academe. Many thanks.

Last I would like to thank Bengt – without you, ofcourse, we would not have had this inspiring and interesting meeting. A special thanks to you and Sigbritt for treating us to such a wonderful concert!

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References

- Antoja T, Figueras F, Fernández D & Torra J 2008 *A&A* **490**, 135–150.
- Arifyanto M I & Fuchs B 2006 *A&A* **449**, 533–538.
- Árnadóttir A S, Feltzing S & Lundström I 2008 *ArXiv e-prints*, *ArXiv:0807.1665* .
- Bensby T, Feltzing S & Lundström I 2003 *A&A* **410**, 527–551.
- Bensby T, Feltzing S & Lundström I 2004 *A&A* **415**, 155–170.
- Bensby T, Oey M S, Feltzing S & Gustafsson B 2007 *ApJ* **655**, L89–L92.
- Bensby T, Zenn A R, Oey M S & Feltzing S 2007 *ApJ* **663**, L13–L16.
- De Rossi M E, Tissera P B, De Lucia G & Kauffmann G 2008 *ArXiv e-prints*, *ArXiv:0806.2872* .
- De Silva G M, Freeman K C, Bland-Hawthorn J, Asplund M & Bessell M S 2007 *AJ* **133**, 694–704.
- Dehnen W 1998 *AJ* **115**, 2384–2396.
- Demarque P, Woo J H, Kim Y C & Yi S K 2004 *ApJS* **155**, 667–674.
- Diemand J, Kuhlen M, Madau P, Zemp M, Moore B, Potter D & Stadel J 2008 *Nature* **454**, 735–738.
- Edvardsson B, Andersen J, Gustafsson B, Lambert D L, Nissen P E & Tomkin J 1993 *A&A* **275**, 101–152.
- Eggen O J 1992 *AJ* **104**, 1906–1915.
- Famaey B, Jorissen A, Luri X, Mayor M, Udry S, Dejonghe H & Turon C 2005 *A&A* **430**, 165–186.
- Freeman K & Bland-Hawthorn J 2002 *ARA&A* **40**, 487–537.
- Fuhrmann K 1998 *A&A* **338**, 161–183.
- Fuhrmann K 2008 *MNRAS* **384**, 173–224.
- Gilmore G & Wyse R F G 2004 *ArXiv Astrophysics e-prints*, *astro-ph/0411714* .
- Gratton R G, Carretta E, Desidera S, Lucatello S, Mazzei P & Barbieri M 2003 *A&A* **406**, 131–140.
- Hänninen J & Flynn C 2002 *MNRAS* **337**, 731–742.
- Holmberg J, Nordström B & Andersen J 2007 *A&A* **475**, 519–537.
- Hopkins P F, Hernquist L, Cox T J, Younger J D & Besla G 2008 *ArXiv e-prints*, *ArXiv:0806.2861* .
- Kim Y C, Demarque P, Yi S K & Alexander D R 2002 *ApJS* **143**, 499–511.
- Matteucci F 2008 *ArXiv e-prints*, *ArXiv:0804.1492* .
- Nissen P E, Primas F, Asplund M & Lambert D L 2002 *A&A* **390**, 235–251.
- Nordström B, Mayor M, Andersen J, Holmberg J, Pont F, Jørgensen B R, Olsen E H, Udry S & Mowlavi N 2004 *A&A* **418**, 989–1019.
- Perryman M A C, Lindegren L, Kovalevsky J, Hoeg E, Bastian U, Bernacca P L, Crézé M, Donati F, Grenon M, van Leeuwen F, van der Marel H, Mignard F, Murray C A, Le Poole R S, Schrijver H, Turon C, Arenou F, Froeschlé M & Petersen C S 1997 *A&A* **323**, L49–L52.
- Read J I, Lake G, Agertz O & Debattista V P 2008 *MNRAS* **389**, 1041–1057.
- Reddy B E, Lambert D L & Allende Prieto C 2006 *MNRAS* **367**, 1329–1366.
- Reddy B E, Tomkin J, Lambert D L & Allende Prieto C 2003 *MNRAS* **340**, 304–340.
- Roškar R, Debattista V P, Quinn T R, Stinson G S, Wadsley J & Kaufmann T 2008 *ArXiv e-prints*, *ArXiv:0807.1942* .
- Sellwood J A & Binney J J 2002 *MNRAS* **336**, 785–796.
- Shapiro K L, Genzel R, Forster Schreiber N M, Tacconi L J, Bouche N, Cresci G, Davies R, Eisenhauer F, Johansson P H, Krajnovic D, Lutz D, Naab T, Arimoto N, Arribas S, Cimatti A, Colina L, Daddi E, Daigle O, Erb D, Hernandez O, Kong X, Mignoli M, Onodera M, Renzini A, Shapley A & Steidel C 2008 *ArXiv e-prints*, *ArXiv:0802.0879* .

- Shapley A E, Erb D K, Pettini M, Steidel C C & Adelberger K L 2004 *ApJ* **612**, 108–121.
- Soubiran C & Girard P 2005 *A&A* **438**, 139–151.
- Springel V, Frenk C S & White S D M 2006 *Nature* **440**, 1137–1144.
- Stockton A, Canalizo G & Maihara T 2004 *ApJ* **605**, 37–44.
- van Leeuwen F 2007 *Hipparcos, the New Reduction of the Raw Data* Astrophysics and Space Science Library, Vol. 350, Springer Dordrecht.
- Venn K A, Irwin M, Shetrone M D, Tout C A, Hill V & Tolstoy E 2004 *AJ* **128**, 1177–1195.
- Williams M 2008 *The Arcturus moving group* PhD thesis Australian National University.
- Yoachim P & Dalcanton J J 2006 *AJ* **131**, 226–249.
- Yoachim P & Dalcanton J J 2008 *ApJ* **683**, 707–721.